Controlled Rolling of H-shapes*

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Synopsis

Controlled rolling on universal mill has been performed of Al-killed steel H-shapes. The experiments have revealed that the portions such as flange, flange edge, fillet and web have variations in deformation behavior and cooling rates during the rolling, depending upon rolling size and aimed finishing temperature. The deformation behavior and cooling rates, together with the finishing temperature affect the mechanical properties of H-shapes through their influences on ferrite grain size and sub-grain structure.

I. Introduction

In producing shapes for low temperature services, the controlled rolling is the most efficient method. However, the heat treatment for this purpose poses difficulty because of the complex profile of the product. On the controlled rolling, many studies have been made as to plate,¹⁻⁷⁾ but few as to shapes. The rolling temperature and reduction for obtaining required strength and toughness must so complexly be changed from portion to portion of the shape being rolled that various factors must be taken into consideration in the controlled rolling of shapes.

This paper describes the controlled rolling of H-shapes performed on the universal mill, together with the effect of deformation pattern and temperature on mechanical properties as investigated at each portion of H-shapes such as web, flange and fillet.

II. Experimental Procedures

In order to understand the mechanism of controlled rolling of H-shapes, the following experiments have been performed using Al-killed steel having simple metallographic behavior during controlled rolling, e.g., recrystallization and precipitation.

1. Steels

Commercial steels with chemical composition shown in Table 1 have been rolled into two typical sizes of H-shapes, e.g., column type: 300×300×10×15, and beam type: 600×200×11×17.

Figure 1 is a schematic diagram of metallographic behavior of Al-killed steel.

A_{r3} transition temperature determined by CCT diagram is 730°C and A_{r1} is 600°C. In actual rolling condition, however, ferrite precipitation begins at higher temperatures because of strain induced transformation.⁸⁾ Therefore, A_{r3} is about 750°C.

The deformation recrystallization cannot be observed at or below 850°C.³⁾ Austenite grain growth after the deformation recrystallization is retarded by

precipitation of AlN below 1 100°C.⁹⁾ Therefore, the equilibrium austenite grain diameter is about 40 μ at 900° to 1 000°C.¹⁾

2. Rolling Conditions

All experimental rollings have been performed on the Wide Flange Beam Mill¹⁰⁾ at Mizushima Works, Kawasaki Steel Corp. With a great emphasis placed on rolling at austenite non-recrystallizing temperature, the rolling conditions are as follows.

- (1) Reheating temperature of beam blanks is 1 250°C.
- (2) BD (Break Down) mill rolling temperature is above 1 100°C because of the mill capacity.
- (3) Temperature of early stage of universal rolling is below 1 100°C, where the austenite grain growth is retarded.
- (4) After holding the material until its temperature reaches the aimed temperature, controlled rolling is performed at finishing temperatures from 850°C to 700°C.

The details of rolling conditions are shown in Table 2. In the controlled rolling of 600×200 size, both the reduction and finishing temperatures were set up at three levels, respectively. In the rolling of 300×300 size, only one reduction level and five finishing temperatures were set up.

As a supplemental condition, the thinner webbed beam blank for 300×300 size with the reduction of web made equal to that of 600×200 size was rolled because of the difference between the two sizes in total reduction of web from beam blank to product.

Table 1. Chemical compositions of steels (%)

Size	C	Si	Mn	P	S	Ni	Al
600×200	0.14	0.18	1.45	0.020	0.006	0.40	0.031
300×300	0.18	0.38	1.47	0.023	0.007	0.02	0.017

Fig. 1. Schematic diagram of metallographic behaviour of Al-killed steel

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Table 2. Rolling conditions

Size (mm)	Reduction (web/flange)						Temperature (°C)	
	Thickness (mm)			Reduction (%)			Heating	Finishing (flange 1/4B)
	After <i>BD</i>	Before <i>CR</i>	<i>P</i>	Total (<i>BB</i> ~ <i>P</i>)	<i>U</i> 1	<i>CR</i> total (1 pass)		
600×200	71.0/110.0	20.0/31.2	11.0/17.0	92/86	72/72	45/45 (16/16)	1 250	850
		18.0/27.9			75/75	39/39 (13/13)		810
		16.0/25.1			77/77	31/32 (10/10)		770
300×300	46.0/90.0	16.4/27.9	10.0/15.0	95/83 91/83	64/69	39/46 (14/16)	1 250	930
								870
								810
								750
								720

BB: Beam blank
BD: Break down mill⁽¹⁰⁾
U1: Universal mill⁽¹⁰⁾

CR: Controlled rolling
P: Product

Fig. 2. Sampling positions of longitudinal test pieces in a cross-section of H-shape

3. Testing

1. Temperature Measurement

The temperature of rolling materials was measured with the following pyrometers.

- 1) Pyroscope (automatic optical pyrometer), IRP, Chino Works, Ltd., fixed type and travelling type
- 2) Thermography, JTG-IA, JEOL

Each pyrometer was calibrated by simultaneous measurement with the pyroscope and a thermocouple or with one another.

2. Sampling Positions of Test Specimens

Each longitudinal test specimens was taken from four positions, e.g., the flange edge, flange, fillet, and web of H-shape as shown in Fig. 2.

3. Test Items

The following tests were carried out: tensile test (circular cross section 5 mm in diameter), 2 mm V-notch Charpy test, and observation of microstructures.

III. Result

1. Controlled Rolling Conditions and Mechanical Properties

1. Actual Rolling Conditions

The relationship between the temperature and reduction at flange during rolling is shown in Fig. 3. Relatively light reduction took place during BD

Fig. 3. Schematic relationship between rolling temperature and reduction at flange

rolling. The temperature drop during pre-final rolling was very small because of heat generation by plastic deformation. Holding time after the completion of pre-final rolling was about 2 min. An example of cooling curves (600×200 and 300×300) on CCT diagram is shown in Fig. 4. Ferrite-pearlite structure was observed in each cooling rate.

2. Effect of Reduction on Mechanical Properties

In 600×200 size, a three-pass equi-reduction was effected using three (16, 13 and 10%) levels of reduction rates for each pass. The purpose of using the fixed pass number was to maintain the rolling time and cooling rates constant. The 16% reduction per pass was almost the upper limit of the mill capacity. Relations of finishing temperature *vs.* lower yield point (LYP), and Charpy transition temperature (*T*_{rs}) at each reduction rate are shown in Fig. 5. LYP and *T*_{rs} change with finishing temperature, but the reduction has little effect on mechanical properties in the range of the present experiment. It will be an important subject in future to increase the number of passes and total reduction of controlled rolling,

Fig. 4. An example of cooling curves (600×200 and 300×300 shapes) on CCT diagram of 600×200 shape

Fig. 5. Influence of reduction and temperature on Charpy transition temperature and lower yield point of flange (600×200 shape)

and to investigate the relationships between reduction and mechanical properties.

3. Effect of Finishing Temperature

Figures 6 and 7 show the relationships of finishing temperature *vs.* LYP, and T_{rs} is 600×200 and 300×300 sizes, respectively. Decreasing the finishing temperature increases LYP and decreases T_{rs} ; the relationships are more remarkable in γ non-recrystallizing region at 850°C or below. Below the A_{r3} , LYP increases sharply. These results are much similar to these of plates,^{4,11,12)} but there is a special feature that both T_{rs} and LYP change at each portion of cross-section even at the same finishing temperature.

(1) Fillet

LYP was low and T_{rs} was high. As the finishing temperature lowered, the strengthening and toughening took place to some extent, but these phenomena were not so remarkable as the changes in mechanical properties of other portions. As seen in 300×300 size, T_{rs} already began to increase at 740°C ; this was considered sufficient to determine that the fillet was apt to embrittle.

(2) Flange Edge

LYP was high and T_{rs} was low. Especially T_{rs} remained low even at higher finishing temperatures,

Fig. 6. Effect of finishing temperature on lower yield point at various positions in H-shape

Fig. 7. Effect of finishing temperature at various positions in H-shape

and it did not increase so sharply even in the $(\alpha + \gamma)$ region as in the case of the other positions.

(3) Flange

The same behavior was seen as in the plate rolling.

(4) Web

At a certain finishing temperature, the T_{rs} of web was nearly equal to the T_{rs} of flange in 600×200 size, but in 300×300 size, T_{rs} of web was lower than that of flange and almost equal to that of flange edge. The result of decreased total reduction of web in 300×300 size is shown in Fig. 7, and in this case the T_{rs} of web is equal to that of flange, same as in 600×200 size. It is considered, therefore, that the difference between T_{rs} at web of 600×200 size and that of 300×300 size is caused by the different total reduction of web.

2. Effect of Rolling Conditions on Ferrite Grain Diameter

The purpose of controlled rolling is grain refining. To investigate the effect of rolling conditions on

ferrite grain diameter (*d*), the test was carried out by optical microscope.

1. Effect of Reduction

Relationships between the reduction of controlled rolling and ferrite grain diameter are shown in Fig. 8. The reduction has no effect on ferrite grain diameter; this is similar to the case of mechanical properties.

2. Effect of Finishing Temperature

Relationships between the finishing temperature and $d^{-1/2}$ are shown in Fig. 9. Decreasing finishing temperature refines the ferrite grain, and the level of refining is influenced by each portion in the cross-

section. In the fillet, ferrite grains are still coarse at low finishing temperature, but in the flange edge they are very fine. The microstructures are shown in Photo. 1.

Fig. 8. Influence of reduction and temperature on mean ferrite grain diameter *d* in flange

Fig. 9. Effect of finishing temperature on reciprocal square root of mean ferrite grain diameter $d^{-1/2}$

ft: Finishing temperature (°C)
d: Mean ferrite grain diameter (μ)
LYP: Lower yield point (kg/mm²)
*T*_{rs}: Charpy transition temperature (°C)

Photo. 1.
Change in microstructures with finishing temperature at various positions in 600×200 shape

Optical microstructures				
Flange edge		Flange	Fillet	Web
Higher finishing temperature				
<i>ft</i>	760	850	890	745
<i>d</i>	16.3	26.6	36.4	18.7
LYP	41.0	37.3	35.3	42.5
<i>Trs</i>	-85	-27.5	-5	-65
Lower finishing temperature				
<i>ft</i>	695	785	805	685
<i>d</i>	14.4	20.3	26.6	21.0
LYP	48.2	39.8	37.3	43.5
<i>Trs</i>	-85	-47.5	-32.5	-67.5

50μ

IV. Discussion

1. Relationships between Ferrite Grain Diameter and Mechanical Properties

1. Lower Yield Stress

Relationships between lower yield stress and grain size for polycrystalline metals are usually described by the Hall-Petch equation (1).^{14,15)}

$$\sigma_y = \sigma_0 + ky d^{-1/2} \dots\dots\dots(1)$$

In Fig. 10, the measured lower yield strengths are plotted as a function of the reciprocal square root of mean ferrite grain diameter ($d^{-1/2}$). In this figure, the finishing temperature of the web in 600×200 size is so low that work hardening is observed. Except the scatter at the web, the lower yield strength corresponds to $d^{-1/2}$ in linear correlation which has the same gradient in both sizes. Therefore, the variation of the lower yield strength can be explained by the ferrite grain size.

2. Charpy Transition Temperature

The values of Charpy transition temperature are plotted in Fig. 11 as a function of $d^{-1/2}$. The relationship between T_{rs} and ferrite grain size is linear in both sizes except the data of the web where the separations frequently occurred. Refining of the ferrite grains decreases T_{rs} . However, the gradient of the T_{rs} vs. $d^{-1/2}$ and the absolute value of T_{rs} are influenced by rolling size. The absolute value of 600×200 size is lower than that of 300×300 size even if the ferrite grain sizes of the two is equal. The gradient of the straight-line is as follows: -29°C per unit of $d^{-1/2}$ in 600×200 size and -19°C in 300×300 size. These gradients are much larger than those calculated from

Eq. (2) by Irani¹⁶⁾ and the experimental data by Matsubara.¹⁷⁾ The former value is -8°C in 600×200 size and -7°C in 300×300 size by counting the pearlite fraction (p): 20% and 25%, respectively, by the point counting method, and the latter value in Al-killed steel is -10°C.

$$T_{rs}(^{\circ}\text{C}) = 36 + \frac{690 - 190d^{-1/2}}{3.5 + p} \dots\dots\dots(2)$$

Therefore, it may be concluded that the transition temperature depends upon ferrite grain diameter qualitatively, but the difference of the gradient and the absolute value in each rolling size depends on some other metallographical factors in addition to ferrite grain diameter as discussed next.

2. Factors Effective on T_{rs}

1. Pearlite Banded Structure

Pearlite banded structure may decrease the T_{rs} as a crack arrester and a crack divider.²⁾ In Fig. 12, the relationship between the transition temperature and the number of pearlite banded structure is shown. In this figure, with an increase in the number of pearlite banded structure, the T_{rs} becomes lower. Many reasons have been proposed concerning the mechanism for the growth of the banded structure. It is confirmed that the band density of banded struc-

Fig. 10. Relation between lower yield point and reciprocal square root of mean ferrite grain diameter $d^{-1/2}$ at various position in H-shape

Fig. 11. Relation between Charpy transition temperature and reciprocal square root of mean ferrite grain diameter $d^{-1/2}$

Fig. 12. Relation between number of pearlite banded structure and Charpy transition temperature

ture is closely connected to the total reduction from the beam blank to the product. In Fig. 12, a decrease of the total reduction of the web of 300×300 size reduces the band density of pearlite banded structure and increases T_{rs} . Therefore, the beneficial effect of increasing the total reduction comes from producing the high band density of the banded structure. However, the effect of the banded structure on T_{rs} resulted in a rather unexplainable residual dispersion or scatter. Because, with an increased band density of banded structure, the ferrite grain is refined, the effect of banded structure on T_{rs} can not be observed individually. A similar result is obtained by means of the multiple regression analysis. We conclude that the difference of the incline and the absolute value concerning the relationship between T_{rs} and $d^{-1/2}$ in each rolling size cannot be explained by means of the beneficial effect of banded structure on T_{rs} .

2. The Unit Crack Path of Brittle Fracture

In order to study other metallographical factors which might effect T_{rs} , the observation of brittle fracture in broken test pieces after Charpy testing was carried out by scanning electron microscope. All test pieces have an amount of about 80% crystallinity. Photograph 2 shows the example of brittle fracture of two different rolling sizes.

The mean unit crack path of brittle fracture for ferrite-pearlite structure is determined by the method of Terasaki and Ohtani.¹⁸⁾ In Fig. 13, T_{rs} values are plotted as a function of the reciprocal square root of mean unit crack path, $(l^{-1/2})$. In this case, the plotted data for both rolling sizes are on the one straight line unlike the case of the relationship between T_{rs} and $d^{-1/2}$. The gradient of linear line is the same as that on Ni-Cr-Mo steel by Kunitake *et al.*¹⁹⁾ Therefore, the gradient of straight line in T_{rs} vs. $d^{-1/2}$ and the absolute value of T_{rs} depend not on

Photo. 2. Examples of the brittle fracture surface and determined mean unit crack path

matrix strength or toughness of each rolling size but on the orientation of neighbouring ferrite grain crystal.

3. Microstructure

The transition temperature usually begins to rise with a certain degree of deformation in $(\alpha+\gamma)$ range. However, the temperature at which T_{rs} elevates changes with various positions in H-shapes. The results suggest that microstructures change with the rolling conditions at various positions in H-shapes.

Fig. 13. Relation between transition temperature and reciprocal square root of mean unit crack path $l^{-1/2}$ at various positions in H-shape

In order to understand the effect of the microstructure on the transition temperature, transmission electron micrographic observations were carried out. Examples of microstructure at various positions are shown in Photo. 3. In this photograph, although the flange edge and the web are deformed in $(\alpha+\gamma)$ range, the flange edge has a recovered structure with a low dislocation density and well-developed subgrains, while the structure of the web is influenced by rolling size. In the 600x200 size, the dislocation density is high and recovery structure is hardly observed because of rapid cooling rate; on the other hand, recovery structure with subgrains is observed in the 300x300 size. The fact that the flange edge is scarcely embrittled is due to the rolling conditions which facilitate the recovery of structure.

3. Effect of Deformation Pattern and Temperature Drop Rate on Mechanical Properties at Various Positions in H-shapes

In order to have a better understanding of the mechanism that the ferrite grain diameter and the microstructure change and hence LYP and T_{rs} alter with various portions of H-shapes even if the finishing temperature is the same, the deformation pattern and temperature drop rate during controlled rolling at various positions of H-shapes are discussed.

1. Deformation Pattern

H-shapes are rolled on the universal mill and edger mill. The former reduces the thickness of flange and

	Flange edge	Flange	Fillet	Web
(a) 600x200	ft 740	825	870	740
(b) 300x300	ft 740	805	840	750

ft: Finishing temperature (°C)

Photo. 3. Transmission electron micrography at various position in H-shape

the web, while the latter regulates the flange width.

It was shown by Kusakabe *et al.*¹³⁾ that the deformation pattern during rolling varied according to positions in H-shapes. In order to closely understand the effects of the edger mill rolling on deformation pattern particularly at flange edge, some samples were taken from H-shapes during the universal and edger mill rolling and examined. The results of deformation pattern at flange edge are shown in Table 3. The deformation pattern at each position is summarized as follows.

(1) Web and Flange

The thickness is reduced in accordance with the pass schedule and the deformation pattern is similar to that in plate rolling.

(2) Fillet

The fillet thickness is not reduced by a direct contact of rolls, but the cross-section is reduced as a result

of the stretch given by the greater elongation of the other positions. (Dead metal-like deformation)

(3) Flange Edge

In this case, expanding of thickness after the edger mill rolling is observed, and hence, the total reduction is larger than that of the flange reduced by only universal mill rolling.

2. Temperature Drop Rate during Controlled Rolling

Controlled rolling is performed through three passes in about 1 min. The cooling rate changes with each portion of H-shapes during the controlled rolling. It is considered that the mechanical properties change with the initial temperature of the controlled rolling even if the finishing temperature is constant. The factors which affect the temperature distribution at various positions of H-shapes during the controlled rolling are shown in Table 4 and summarized as follows.

(1) Initial Temperature before Controlled Rolling

The initial temperature of controlled rolling changes with the temperature drop occurred by thermal radiation during holding. At the flange edge, the area for radiation is wide and little thermal radiation heat from the other positions is observed, then, the cooling rate is more rapid and initial temperature is lower than in the other position. Because of its thin thickness, thermal radiation can easily occur at the web and then, the cooling rate is large. Concerning the rate of thermal radiation at the web, however, it is slower for the column type than for the beam type owing to the larger amount of thermal radiation heat from flange. Then, the initial temperature of the web in the column type is higher than in the beam type.

(2) Temperature Drop during Rolling

During the controlled rolling, two factors, *i.e.*, the temperature drop by the roll coolant and the temperature rise by plastic deformation must be considered in addition to the thermal radiation mentioned before.

At the flange edge, the temperature drop decreases with increasing the deformation on U1 (roughing universal) mill and on E1 (edger) mill, and hence with increasing the recuperation.

At the web, the temperature drop is large because

Table 3. Influences of edger and universal rolling on reduction in the flange edge (300×300 shape)

Pass No.	Roll- ing	Thickness (mm)		Width (mm) C, C'	Reduction (%)		
		A	B, B'		Thickness		Width
					A	B, B'	
8	U1	27.9	27.9	310			
9	U1	23.4	23.4	310	16.1	16.1	10.0
	E1	23.4	26.7	305			
10	U1	19.6	19.6	305	16.2	26.6	
11	U1	16.4	16.4	305	16.3	16.3	8.0
	E1	16.4	18.3	301			
12	Uf	15.0	15.0	301	8.5	18.0	
Total					46	58	17

Uf: Final universal rolling

Table 4. Temperature drop rate at various positions in H-shape

Position		By radiation during holding		Initial temperature of <i>CR</i>	During <i>CR</i>				
		Dependent on thickness	Dependent on shape		By radiation		By roll coolant	By recuperation	Total
					Dependent on thickness	Dependent on shape			
Flange edge		0	+	Much lower	0	+	0	—	—
Flange		B	B	B	B	B	B	B	B
Fillet		0	—	Higher	0	—	0	+	0
Web	Column type	+	—	Lower	++	—	++	0	+
	Beam type	+	0	Much lower	++	+	++	0	++

CR: Controlled rolling
B: Basic level for each item
0: Same as base

+ : Larger than base
— : Smaller than base
++ : Much larger than base

the roll coolant trends to stay and the thickness is still reduced. However, owing to the shape factor, the temperature drop rate of web in the column type is smaller than in the beam type. At the flange and fillet, the temperature drop rate is midway between the flange edge and the web.

From these analyses, it may be concluded that the flange edge has fine ferrite grains and a higher strength and toughness according to deformation on U1 mill after E1 mill and on E1 itself and also according to isothermal deformation. The fillet has coarse ferrite grains, a lower strength and toughness because it is in dead metal like deformation.

V. Rolling Model Experiments

In order to confirm the effects of the deformation pattern and temperature drop rate on the ferrite grain size, model experiments were carried out. The test procedures and results are shown in Figs. 14, 15 and 16, respectively.

1. Materials and Experimental Procedure

The test pieces 25 mm cubic were cut from the same heat material as rolled into 300×300 H-shapes, and normalized at 910°C. After reheating at 950°C, the five different deformation modes as shown in Fig. 16 were examined according to the specified temperature and deformation pattern corresponding to each position in H-shapes, and then the ferrite grain size was examined by optical microscope.

Cooling rate of the 25 mm cubic test specimens was controlled with asbestos cloth to obtain the ferrite-pearlite structure as shown in Fig. 15, but these cooling

Type	Corre- sponding position	Deformation procedure
A	Web or flange	(25×25) → (12.8×35.0)
B	Fillet	(25×25) → (21.2×21.2)
C	Flange edge	(25×25) → (12.8×25.0)

— Deformation plane
() Cross section (mm)

Fig. 14. Deformation types in model experiment

Fig. 15. Cooling curve of 25 mm cubic specimen on CCT diagram (cf. Fig. 3)

rates were relatively larger than that of the product 300×300 size, and then the ferrite grain size was finer compared with that of the product. In this model experiment, the followings were in consideration.

1. Deformation Procedure

The following three different procedures were carried out.

(Type A) Flange, Web Type: Deformation was carried out parallel to thickness direction.

(Type B) Fillet Type: Deformation was carried out so as to maintain the square section by alternate reductions, i.e., “Horizontal-Vertical-Horizontal”. The decrease of cross-sectional area was equal to the flange, web type.

(Type C) Flange Edge Type: The vertical reductions were added to (Type A), and finally the width of the test piece was kept 25 mm. (In Type A, the test piece was 35 mm in width.)

2. Cooling Rate during Deformation

(Case A) One heat time deformation

(Case B) Three heat times deformation to obtain the

	Deformation pattern (type)	Microstructure 10 μ
I	(A) Temp. (°C) 910 790 A _{r3} Deformation step
II	(B) Temp. (°C) 910 790 A _{r3} Deformation step
III	(C) Temp. (°C) 907 760 A _{r3} Deformation step
IV	(B) Temp. (°C) 873 (Lower finish. temp.) 742 A _{r3} Deformation step
V	(Isothermal) (B) Temp. (°C) 800 820 740 A _{r3} Deformation step

Fig. 16. Effect of deformation modes on microstructures

isothermal condition

2. Test Results and Discussion

The ferrite grain sizes are shown in Fig. 16. The three different deformation patterns, I, II and III, make the three different ferrite grain sizes, respectively. Flange edge type deformation (Mode III) made the finest ferrite grain and fillet type deformation (Mode II) gave the most coarse ferrite grain. Isothermal deformation (Mode V) made a smaller ferrite grain than continuous cooling deformation (Mode IV).

It was found from the deformation model experiments that the ferrite grain size at each position even if finishing temperature is the same may be influenced by the deformation pattern and the cooling rate during controlled rolling.

For improving the mechanical properties of the fillet where the ferrite grain is coarse owing to dead metal-like deformation, a large amount of reduction is necessary. However, the amount of reduction is limited by rolling mill capacity. The finishing temperature at the flange edge is often near A_{r3} , then isothermal conditions are easily achieved because of latent heat due to γ - α transformation.

VI. Summary

Controlled rolling of low C, Al-killed steel of H-shapes on universal mill is performed and the relations between rolling conditions and mechanical properties are investigated. The main results are summarized as follows:

(1) Decrease in the finishing temperature changes LYP and T_{rs} . However, the rate of change varies by each position in cross-section, and the values of LYP and T_{rs} are different even at the same finishing temperature.

(2) The ferrite grain diameter " d " changes with finishing temperature. The variation of " d " corresponds to LYP and T_{rs} .

(3) As a measure for the quantitative evaluation of the T_{rs} , the mean unit crack path is more suitable than ferrite grain diameter. In order to understand the mechanism of the change of T_{rs} , the detailed investigations about the neighbouring ferrite grain orientation are necessary. Various embrittlements at $(\alpha+\gamma)$ temperature at each portion can be explained by the difference of the amount of recovered microstructures.

(4) The difference of ferrite grain diameter and microstructure between each portion of cross-section is caused by the difference of deformation pattern and temperature drop rate during controlled rolling. Details are as follows:

(a) Flange edge: Fine grain, higher strength and toughness because of the large amount of isothermal deformation and little embrittlement at $(\alpha+\gamma)$ temperature.

(b) Fillet: Coarse grain, lower strength and

toughness because of dead metal-like deformation. Even at decreasing finishing temperature, the rate of grain refining is small, and the steel is severely embrittled by the reduction at $(\alpha+\gamma)$ temperature.

(c) Flange, Web: Plate like deformation and medium strength and toughness between flange edge and fillet. However, mechanical properties at the web are influenced by rolling size because of the total reduction from beam blank to product and temperature drop rate during controlled rolling.

(5) The controlled rolling conditions at each portion in cross-section are complexly changed by rolling size and specified finishing temperature.

In order to obtain H-shapes for low temperature use by controlled rolling, the following items are important:

(a) Finishing temperature distribution in cross-section of each rolling size.

(b) Total reduction from beam blank to product at each portion of cross-section.

(c) Deformation pattern and temperature drop rate at each portion of cross-section during controlled rolling.

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